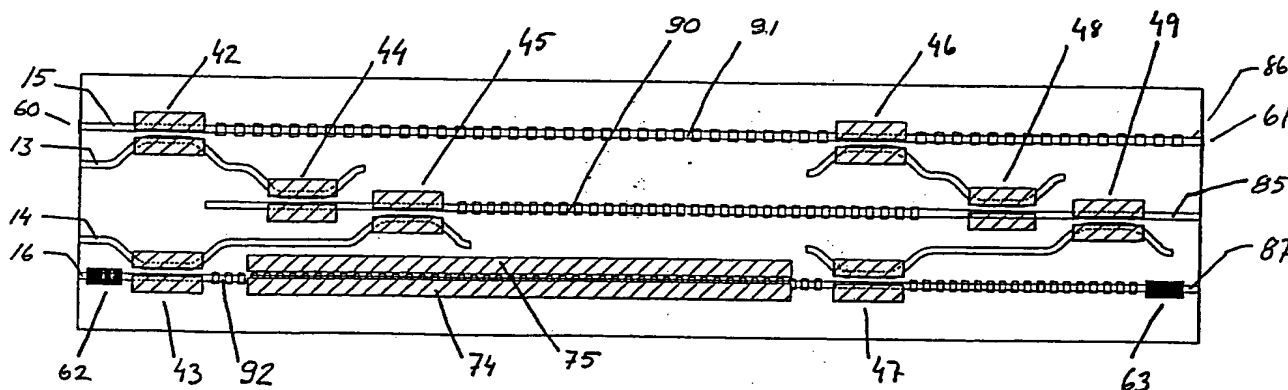




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(54) Title: LIGHT SOURCE**(57) Abstract**

The present invention concerns a coherent light source based on frequency conversion of the radiation from two lasers (20, 21) by frequency mixing in optical waveguides (10; 90), which are provided in a substrate (1). The wavelengths for the two lasers (20, 21) should be such, that the phase matching condition for the optically nonlinear frequency conversion is fulfilled in the waveguide structure (10; 90). The frequency conversion is accomplished in the form of frequency mixing, frequency doubling or down conversion in frequency by parametric oscillation so that in total three or four new wavelengths can be generated. By using integrated optics technique the output radiation can be controlled in various ways, for example be switched to different output waveguides, varied in intensity or colour balance.

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Light source

2 The present invention relates to light sources which
3 are based on frequency conversion of radiation from lasers
4 with moderate output powers, such as semiconductor lasers.

5 It is of great interest to construct small, compact,
6 power efficient, narrow linewidth, and inexpensive light
7 sources in the visible wavelength range. Small efficient
8 light source are available in the near infrared wavelength
9 region in the form of semiconductor lasers. With some
10 difficulty also semiconductor lasers emitting in the
11 visible part of the spectrum can be made. Primarily the
12 value of the bandgap in the semiconductor material limits
13 the possibility to generate shorter wavelengths. In the
14 same way there exist a large interest for compact and
15 power efficient light sources at longer wavelengths in the
16 infrared, than is obtainable with regular semiconductor
17 material.

18 Research is under way on different semiconductor
19 materials to try to develop compact and reliable light
20 sources at new wavelengths, but many problems remain to be
21 solved.

22 An alternative approach to reach new wavelengths is to
23 use nonlinear effects, as frequency doubling,
24 sum-frequency generation, difference-frequency generation
25 and parametric oscillation for frequency conversion of
26 available laser frequencies. Especially frequency doubling
27 is a common method to generate new wavelengths from
28 certain high power laser systems, which are used
29 particularly in research laboratories. For lasers with
30 moderate output powers this method is more difficult to
31 apply, primarily because the conversion efficiency for
32 frequency conversion is too low in this case.

33 To obtain a satisfactory conversion efficiency for
34 nonlinear processes, such as frequency doubling and
35 sum-frequency generation, high intensities are required

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1 over comparatively long interaction lengths. By using an
2 optical waveguide, especially a so-called channel
3 waveguide, a focused laser beam can be confined within a
4 small cross section area (and thereby high intensity) over
5 long interaction lengths without being diffracted. This
6 means that in a waveguide provided in a good optically
7 nonlinear material, it can be possible to obtain a high
8 conversion efficiency even for lasers with low output
9 power. The primary limiting factor for practical
10 applications is that the so-called phase-matching
11 condition must be fulfilled.

12 Lithium niobate (LiNbO_3) is a material that has a
13 comparatively high nonlinearity and in which it is also
14 possible to fabricate waveguides of high quality and long
15 lengths (several cm).

16 The so-called phase-matching condition, which must be
17 fulfilled to achieve an efficient wavelength conversion,
18 can for frequency mixing (sum- or difference-frequency
19 generation) be written:

20
$$k_3 = k_1 \pm k_2 \quad (1a)$$

21 or equivalently:
$$\frac{2\pi N_{\text{eff},3}}{\lambda_3} = \frac{2\pi N_{\text{eff},1}}{\lambda_1} \pm \frac{2\pi N_{\text{eff},2}}{\lambda_2} \quad (1b)$$

22 with:
$$\frac{1}{\lambda_3} = \frac{1}{\lambda_1} \pm \frac{1}{\lambda_2} \quad (2)$$

23 where λ_1 and λ_2 are the two pump wavelengths ($\lambda_1 \leq \lambda_2$),
24 while λ_3 is the generated wavelength, and whereby the plus
25 sign corresponds to sum-frequency generation and the minus
26 sign to difference frequency generation. $N_{\text{eff},1}$, $N_{\text{eff},2}$ and $N_{\text{eff},3}$
27 are the so-called effective refractive indices in the
28 waveguide at these three wavelengths, respectively. In the
29 special case of frequency doubling, the plus sign applies
30 together with $\lambda_1 = \lambda_2$ and $N_{\text{eff},1} = N_{\text{eff},2}$. Phasematching means that
31 the generated radiation is propagating with the same phase
32 velocity as the driving nonlinear polarization. The phase

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1 velocities are determined by the effective indices, and to
2 fulfil the phase matching condition the refractive indices
3 at the three wavelengths must comply with the condition
4 given by equation (1b). In the case of frequency doubling
5 this corresponds to equal effective indices at the
6 fundamental and the frequency doubled wavelength. The same
7 equations are valid for parametric oscillation, provided
8 that the plus signs are used and that λ_3 corresponds to the
9 pump wavelength, whereas λ_1 and λ_2 correspond to the
10 generated wavelengths. In the case of degenerated
11 parametric oscillation only one wavelength is generated,
12 i.e. $\lambda_1 = \lambda_2$.

13 To achieve phasematching in waveguides most often the
14 birefringence of the material is utilized, whereby the
15 interacting waves are differently polarized. For
16 sum-frequency generation in lithium niobate (LiNbO_3) the
17 light at the two pump wavelengths experience the
18 polarization corresponding to the ordinary refractive
19 index while the generated wave is experiencing the
20 extraordinary polarization. From the dispersion curves for
21 the ordinary and the extraordinary refractive indices of
22 LiNbO_3 , schematically shown in Fig.1, it can be seen that
23 only wavelengths around 540 nm can be generated by
24 frequency doubling and sum-frequency generation. However,
25 a certain amount of tunability can be obtained by a
26 different choice of the two pump wavelengths used in
27 sum-frequency generation or by varying the temperature of
28 operation. In the first case the nonlinearity of the
29 dispersion curve is used, while the second case relies on
30 different temperature dependency for the ordinary and the
31 extraordinary refractive indices. One can also obtain some
32 wavelength shift by doping of the substrate for instance
33 with MgO or proton exchange and by changing the design of
34 the waveguide (which affects the waveguide dispersion).
35 It is well-known that waveguides in LiNbO_3 are suitable for

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1 frequency doubling as well as for sum-frequency
2 generation, difference-frequency generation, parametric
3 oscillation and parametric amplification. In such
4 experiments, however, almost exclusively gas lasers and
5 solid-state lasers have been used. For example, it has
6 been demonstrated that, with radiation from a Nd:YAG laser
7 (1.064 μm wavelength), high conversion efficiency for
8 frequency doubling can be obtained at relatively low pump
9 powers in lithium niobate waveguides, fabricated in either
10 doped or undoped substrate material. Frequency doubling in
11 lithium niobate waveguides according to this scheme has,
12 however, not yet been applied for semiconductor lasers due
13 to the phase-matching difficulties.

14 Today reliable semiconductor lasers are available
15 primarily in three wavelength regions: around 0.8 μm
16 (based on GaAs), around 1.3 μm (based on InP) and around
17 1.55 μm (based on InP). None of these wavelengths can be
18 phase-matched for frequency doubling in conventional
19 lithium niobate-waveguides.

20 However, it is known that radiation from diode lasers
21 at wavelengths around $\lambda \approx 0.8 \mu\text{m}$ can be frequency doubled
22 in so-called proton exchanged waveguides, with the
23 frequency doubled light generated in the form of Cerenkov
24 radiation. The light is then generated as a radiation mode
25 propagating into the substrate. It has been possible to
26 construct a small compact light source this way, with the
27 wavelength in the visible range. A disadvantage with this
28 technique, is that the nonlinear process is less efficient
29 as compared to the case when coupling takes place between
30 two guided waves. Another disadvantage is that waveguide
31 cross-section has to be extremely small in practice. This
32 leads to very high light intensities in the waveguide and
33 a tendency to light induced changes in the waveguide that
34 detrimentally affect the stability of the frequency

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1 doubling, especially at continuous wave operation. The
2 light is also emitted in a cone under the waveguide, which
3 makes it difficult to collimate and focus the light.

4 Another known technique for frequency conversion in
5 waveguides is to utilize so-called quasi-phase-matching in
6 periodically domain inverted waveguides in LiNbO_3 or LiTaO_3
7 (lithium tantalate). Quasi-phase-matching is a more
8 generally useful phase-matching method because the
9 possibility to achieve phase-matching is not limited by
10 the amount of the birefringence in the material. It is,
11 however, technically more difficult to fabricate the
12 required waveguide structure. Quasi-phase-matching
13 waveguides can be used to frequency double, for instance
14 $0.85 \mu\text{m}$ and $1.3 \mu\text{m}$ wavelengths, thereby generating blue
15 and red light, respectively. Quasi-phasesmatched frequency
16 doubling can not be used to generate green light, however,
17 due to shortage of semiconductor lasers at the required
18 fundamental wavelength.

19 It is also known that appropriate/adequate/relevant
20 nonlinear optical materials, such as LiNbO_3 , LiTaO_3 , KTP (KTiOPO_4),
21 KNbO_3 (potassium niobate) etc., also have high
22 electro-optical material coefficients, and that
23 consequently the electro-optic effect advantageously can
24 be used for steering/control/switching and modulation of
25 the light. There are known methods to control light by
26 using various integrated optical components, for example
27 in order to couple part of the light from one channel
28 waveguide to another either in a fixed, predetermined way
29 or in a varyable way, or in order to modulate the
30 intensity, phase or phase velocity of the light in a
31 channel waveguide.

32 There are known methods based on the use of various
33 integrated optical components for controlling light
34 (propagating in a channel waveguide) for example for
35 coupling part of the light from one channel waveguide to

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1 another either in a fixed predetermined way or in a
2 variable way and for modulationg the intensity, phase or
3 phase velocity of the light in a channel waveguide.

4 Metal electrodes arranged on the crystal surface,
5 either on top of the waveguide or beside it, to which
6 electric drive voltage are applied, are used for
7 adjustment and modulation. Modulation using the
8 electro-optic effect can be done with low drive voltage
9 and high modulation frequency, and no mechanically mobile
10 parts are required. It is also known that many integrated
11 optical components, active as well as passive, are
12 wavelength selective.

13 To be able to realize a small, semiconductor laser
14 pumped frequency doubler based on conventional waveguides
15 in LiNbO_3 , requires a comparatively powerful diode laser at
16 a wavelenght of around $1.08 \mu\text{m}$. It is only this
17 wavelength (approximately), that can be phasematched for
18 frequency doubling in LiNbO_3 waveguides at room temperature
19 and today such lasers are not available.
20 Corresponding restrictions to a narrow (wavelength)
21 interval for the fundamental wavelenth(s), for which
22 frequency doubling can be achieved in practice, applies
23 also to other nonlinear materials as KNbO_3 , KTP , LiTaO_3 ,
24 BBO ($\beta\text{-BaB}_2\text{O}_4$), LBO (LiB_3O_5), etc. This illustrates the main
25 problem with frequency conversion, which is to solve the
26 phase-matching problem in a way as general as possible in
27 order to be able to utilize available laser frequencies
28 and nonlinear materials.

29 One prerequisite/condition is that today, diode lasers
30 that are easily available, single mode, have long life
31 (time?), and relative high output powers mainly exist at
32 three limited wavelength regions: 780-850 nm (based on
33 GaAs) and around 1300 nm and 1550 nm (in both the latter
34 case based on InP substrates).

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1 To be able to integrate light sources of different
2 wavelengths on the same substrate, would be of great value
3 for many applications like displays, optical scanning,
4 optical registration, image generation etc.

5 For a number of applications is it further of great
6 interest to have a possibility to easily modulate the
7 intensity of the light source and/or to select its
8 wavelength from a number of alternative wavelengths, or to
9 change the color balance of the light source, by varying
10 the relative intensities of a number of different
11 wavelength components included in the light source.

12 The purpose of the present invention is to accomplish
13 compact light sources, particularly in wavelength regions
14 where no semiconductor lasers are available, by efficient
15 frequency conversion of radiation from semiconductor
16 lasers (or other compact, power efficient lasers) in
17 waveguides, and thereby in a flexible way solve the
18 phase-matching problem so that as many wavelengths as
19 possible can be generated from available laser wavelengths
20 and available nonlinear optical materials. The purpose is
21 also to enable generation of several wavelengths from the
22 same device (the same substrate) and easily with
23 electrical control signals be able to modify the
24 properties of the light source: select one wavelength from
25 a number of available wavelengths, vary the color balance
26 between a number of wavelengths that the light source
27 consists of, modulate the intensity of the light source
28 rapidly etc.

29 The invention provides solutions to the present
30 problems in the way described in the characterizing parts
31 of the five patent claims enclosed. Here it is assumed
32 that a waveguiding structure is arranged in an optically
33 nonlinear material as LiNbO_3 , doped LiNbO_3 , LiTaO_3 , KTP,
34 KTiOAsO_4 , KNbO_3 , BBO, LBO, NYAB or corresponding
35 substances, and that efficient frequency conversion can be

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1 accomplished in this waveguide structure, due to the fact
2 that the radiation for all the wavelengths present can be
3 confined within a small cross-section area over a
4 comparatively long interaction length (several cm).

5 The invention is characterized in that two
6 semiconductor lasers (or other low power lasers) are used
7 to pump the nonlinear frequency mixing process (sum- or
8 difference-frequency generation), whereby the lasers used
9 have such wavelengths that the phase-matching condition is
10 fulfilled either by utilization of the birefringence of
11 the material in combination with the waveguide dispersion
12 or by utilization of so-called quasi-phase-matching
13 technique.

14 The invention is further characterized by the fact that
15 the same device can yield radiation at several
16 wavelengths, due to the fact that apart from the new
17 frequency generated by frequency mixing, also both of the
18 pump frequencies are available, as well as due to the fact
19 that each of these two pump frequencies can separately,
20 and preferably in separate channel waveguides, be
21 frequency doubled or down converted in frequency through
22 parametric oscillation (or through the special case of
23 degenerate parametric oscillation).

24 The invention is also characterized by the
25 possibility to combine the channel waveguides where the
26 frequency conversion takes place, with integrated optical
27 components, based on known technique, which components can
28 be wavelength selective and preferably electro-optically
29 controllable, to adjust the fulfilment of the
30 phase-matching condition and couple the radiation into,
31 out of, or between channel waveguides, in such a way that
32 with electrical control signals it is possible to vary the
33 properties of the light source (alternatively it is
34 possibly to design a device with certain predetermined
35 properties) in one or several of particularly the

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1 following regards: select one wavelength from a number of
2 available wavelengths (which include both the two pump
3 wavelengths as well as the new wavelengths generated in
4 the device), separate and direct the radiation of
5 different available wavelengths to different output
6 channel waveguides and modulate the intensity at each
7 wavelength, combine and direct light of different
8 wavelengths into one common output channel waveguide or
9 into adjacent output waveguides, control the relative
10 intensities or the color balance between a number of
11 wavelength components comprised in the light source. A
12 special case is when the integrated optical components are
13 designed for fixed, predetermined functions.

14 For phasematching based on the use of birefringence the
15 material dispersion and waveguide dispersion together with
16 the temperature dependence of the refractive indices at
17 the wavelengths involved, determines which wavelengths
18 that can be phase-matched by equation (1) and (2).

19 For quasi-phasematching the relation between the
20 wavelengths is still given by equation (2). Equation (1)
21 does not have to be fulfilled, and instead the
22 phase-mismatch which is present, is compensated for, in
23 the known way, by an appropriately chosen periodicity of
24 the quasi-phasematching waveguide.

25 The invention includes a combination of different
26 elements, each of which when taken separately corresponds
27 in many cases to known technique. However, the invention
28 is also based on a thorough analysis, both theoretical and
29 experimental, to define combinations that are of practical
30 interest, and to determine under which conditions these
31 are realistic.

32 We have for instance from calculations found that
33 sum-frequency generation can be obtained between GaAs
34 lasers and InGaAsP lasers at temperatures around, and just
35 above, room temperature in waveguides fabricated by

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1 titanium indiffusion in LiNbO_3 (in undoped and MgO doped
2 crystals). Using two such lasers (operating at or close to
3 two commonly occurring wavelengths: $0.85 \mu\text{m}$ and $1.3 \mu\text{m}$ or
4 $1.55 \mu\text{m}$, respectively) and a LiNbO_3 waveguide, it is
5 possible to build a small, compact coherent source
6 generating visible (green) radiation, which is of great
7 practical interest. We have also demonstrated this
8 principle in a laboratory experiment by mixing radiation
9 from two diode lasers at $0.85 \mu\text{m}$ and $1.31 \mu\text{m}$ wavelengths
10 in a channel waveguide fabricated by titanium indiffusion
11 in lithium niobate and thereby generated light at 0.508
12 μm . In this experiment the birefringence of the material
13 together with the waveguide dispersion was used to fulfil
14 the phase-matching condition. By in this way using
15 sum-frequency generation the invention makes it possible
16 to fulfil the phase-matching condition at a temperature
17 close to room temperature, using available materials and
18 semiconductor laser wavelengths, in cases where the
19 phase-matching condition for frequency doubling of the
20 individual laser wavelengths were not possible, as well as
21 makes it possible to generate green light from
22 semiconductor lasers which has not been possible by
23 frequency doubling because of the lack of laser diodes at
24 an appropriate wavelength.

25 Another application example is that according to the
26 invention the sum-frequency generation can also be
27 combined with frequency doubling of radiation from the two
28 individual pump sources separately, so that for instance
29 if two infrared laser diodes are used as pump sources the
30 possibility exist to generate three different wavelengths
31 in the visible within the same substrate. If two
32 semiconductor lasers at wavelengths around $0.85 \mu\text{m}$ and 1.3
33 μm , respectively, are used, then three different
34 wavelengths can be generated in the visible: namely blue
35 and red by frequency doubling and green through

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1 sum-frequency generation. Obviously many applications
2 exist for such a light source giving both blue, green and
3 red light.

4 The invention is described in closer detail below with
5 reference to the attached figures 2 - 15.

6 Figure 2 shows the invention in one of its simplest
7 embodiments (embodiment 1). A channel waveguide 10 is
8 fabricated in the surface layer of a substrate 1 of an
9 optical nonlinear material. Radiation from two laser
10 diodes 20 and 21, are combined via the lenses 30 and 31
11 and a wavelength selective beam splitter 32 and are then
12 coupled by a lens 33 into the channel waveguide 10 in the
13 substrate 1. The light at the new wavelength generated in
14 the waveguide is passing out through the output end-face
15 of the channel waveguide, possibly together with
16 nonconverted radiation at the two pump wavelengths. The
17 two latter wavelengths can, if desired, be excluded, with
18 an optical component 34, in the form of a filter or a
19 polarizer, at the output end-face of the channel
20 waveguide.

21 The radiation from the two pump sources can be combined
22 and launched into the channel waveguide where the frequency
23 conversion takes place, in a number of ways. The most
24 obvious method is to use a dichroic beamsplitter 32 which
25 transmits one of the wavelengths and reflects the other,
26 as already described and as illustrated in Fig 2.
27 Examples of other methods to combine the radiation are
28 given in Figs. 3 - 5. All the Figures 2 - 5 exemplify
29 different versions of embodiment 1 of the invention.

30 Figs. 3 and 4 show versions, relying on couplers
31 integrated in the waveguide substrate. In Fig. 3 the light
32 from the two channels 13 and 14 are geometrically brought
33 together through a coupler 40 (a Y-coupler) into the
34 common main channel waveguide 10.

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1 In Fig. 4, a wavelength selective coupler of known type
2 is used, with the design parameters chosen so that the
3 radiation propagating in both of the two incoming channel
4 waveguides 13 and 14 are efficiently coupled into the
5 common straight main waveguide 10, where the nonlinear
6 frequency conversion is accomplished. The wavelength
7 selective coupler is in the figure illustrated in the form
8 of a directional coupler (with the interaction length
9 chosen to get the desired coupling), but also other types
10 of integrated optical couplers according to known
11 technique can be utilized (e.g. Mach-Zehnder
12 interferometers, symmetric or asymmetric X-switches,
13 TIR-switches, BOA-couplers, three-waveguide-couplers,
14 combinations of directional couplers and Mach-Zehnder
15 interferometers, Y-switches, so-called digital switches
16 etc.). To modify the degree of coupling in the coupler,
17 the electro-optic effect can be used.

18 In both these cases the diode lasers could be mounted
19 just in front of the crystal and microlenses can then be
20 used to launch the light into the channel waveguides
21 through their end-faces. An alternative is so-called
22 butt-coupling whereby the laser diodes are mounted in
23 close proximity to the end-faces of the channel waveguides
24 and the radiation is coupled directly into the guides
25 without the use intermediate optics. The light could as
26 well be launched through short pieces of optical fibers
27 (so-called fiber pigtails).

28 Alternatives to a filter or polarizer (34 in Fig. 2) in
29 order to eliminate the pump wavelengths, are an integrated
30 optical polarizer, a polarization absorber or another
31 integrated optical wavelength selective component.

32 A third version illustrated in Fig. 5 relies on a
33 fiber-coupler 51 that combines the radiation from the two
34 lasers 20 and 21 whereby the radiation from each laser is
35 launched into one of the two input fibers 52 and 53, and

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1 the common output fiber 54 is mounted ("pigtailed")
2 against the LiNbO₃ substrate or the radiation from this
3 fiber 54 is coupled into the channel waveguide by other
4 means. The state of polarization must be well controlled
5 which may require the use of polarization maintaining
6 fiber. Furthermore, the fiber should be single mode at
7 both pump wavelengths. The end of the fibers, into which
8 the radiation from the lasers are launched can be tapered
9 to increase the coupling efficiency.

10 As mentioned above, an integrated coupler, as number 41
11 described in connection to Fig. 4, can be tuned
12 electro-optically to obtain the exact desired degree of
13 coupling. This technique can also be utilized for
14 modulation of the radiation. One embodiment of the
15 invention (embodiment 2) which utilizes electro-optically
16 controlled couplers are illustrated in Figs. 6 - 9. The
17 individual couplers are provided with metal electrodes,
18 and electric voltages are applied to these in order to
19 control the degree of coupling at the two wavelengths. One
20 arrangement for such electrodes are schematically
21 illustrated for the coupler 42 in Fig. 6 and the couplers
22 42 and 43 in Fig. 7. The arrangement in Fig. 7 gives, as
23 compared to the arrangement in Fig. 6, better
24 possibilities to independently vary the degree of coupling
25 from each light source through the input waveguides 13 and
26 14, respectively, into the main waveguide 10. The couplers
27 are illustrated in the form of directional couplers with
28 two metal electrodes 70 and 71 (72 and 73). To facilitate
29 the control of the coupler, the electrodes might be
30 designed differently, for instance divided into several
31 sections along the channel waveguides. Furthermore there
32 exist, as mentioned previously, a large number of
33 alternative types of couplers or switches. The
34 electro-optic control is also of importance to reduce the
35 fabrication tolerances for a coupler. One can in this way

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1 obtain the desired degree of coupling in spite of a small
2 fabrication error, by applying a correction voltage. A
3 coupler can also be used to modulate the generated light.
4 The generated light can for instance be pulsed in time
5 even though the two diode lasers are radiating
6 continuously.

7 In a special version, illustrated in Figs. 8 and 9, of
8 the second embodiment, the radiation is brought together
9 from the incoming waveguides (13 and 15 in Fig 8 and 13
10 and 14 in Fig 9) into the main waveguide 10, as well as
11 coupled out from the main channel waveguide 10 to the
12 adjacent output waveguides 80 and 81, by the use of
13 electro-optically controlled integrated optical
14 couplers/modulators 42, 43, 44, 45 (which are wavelength
15 selective). The invention is characterized in that the
16 radiation which is then emitted from the main channel
17 waveguide through output 85, can be chosen with electrical
18 control signals to consist of one or several of three
19 wavelengths (the wavelength generated by the frequency
20 mixing, and the two pump wavelengths), and furthermore
21 characterized in that the amplitude of the radiation can
22 be modulated electrically. This embodiment also provides a
23 possibility to separate the three available wavelengths
24 and to obtain each of these separately in three different
25 output channel waveguides 80, 85 and 81, respectively.

26 In cases when the frequency generation can not be
27 phase-matched using birefringence, there is instead a
28 possibility (according to a third embodiment of the
29 invention, illustrated in Figs. 10 and 11) to utilize for
30 the frequency mixing a so-called quasi-phase-matching
31 waveguide 90, for which the periodicity has been chosen as
32 required for the desired frequency mixing process,
33 according to known technique. See Figs. 10 and 11, which
34 besides the use of a quasi-phase-matching waveguide, are
35 identical to Figs. 8 and 9.

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1 A fourth embodiment implies that the so-far described
2 frequency mixing of two laser sources is combined with
3 frequency doubling or down conversion in frequency through
4 (degenerated) parametric oscillation of the radiation from
5 each of the two pump lasers separately, preferably in
6 separate channel waveguides on the same substrate, whereby
7 primarily but not necessarily quasi-phase-matching
8 technique is utilized. See Figs. 12 and 13. Radiation from
9 the two semiconductor lasers (launched into the input
10 waveguides 13 and 14) can then both be coupled into a
11 channel waveguide 90 where sum- or difference frequency
12 takes place, and radiation from each semiconductor laser,
13 or part of their power, can also be coupled into the separate
14 channel waveguides, 91 and 92 respectively, for frequency
15 doubling or parametric oscillation. If two semiconductor
16 lasers with wavelengths around 0.85 and 1.3 μm are used,
17 radiation at three different wavelengths in the visible
18 range can be generated in this way: blue and red light by
19 frequency doubling of the wavelengths 0.85 and 1.3 μm ,
20 respectively, and green light by sum-frequency generation.
21 It is further illustrated schematically in Figs. 13 and 14
22 how the output channel waveguides 86, 85 and 87 can be
23 brought close together, so that at the output they
24 together form a small light source, in which the intensity
25 at the three wavelengths and the balance between them can
26 be controlled electro-optically and at high speed. In Fig.
27 13 the output channels have been placed comparatively
28 close, but so that coupling not necessarily occurs between
29 them; instead each one emits radiation at a specific
30 wavelength and the farfield pattern for each wavelength
31 can thus be controlled by the design of the corresponding
32 waveguide. As illustrated in Fig. 14 the radiation at the
33 three wavelengths can alternatively be brought together
34 into one common output channel waveguide 85 using
35 integrated optical couplers 46, 47, 48, 49, so that a true

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1 point light source is obtained (common for all the
2 wavelengths), in contrast to the version illustrated in
3 Fig 13.

4 Integrated optical components in combination with other
5 channel waveguides can further be used to separate out
6 undesired parts of the power spectrum at the pump
7 wavelengths, in analogy with Fig 8.

8 For all the embodiments of the invention the exact
9 phase-matching can be accomplished by temperature tuning
10 of the nonlinear crystal according to known techniques
11 (for instance using Peltier elements), possibly together
12 with electro-optic tuning using metal electrodes along the
13 waveguides. For the lower channel waveguide 92 in Fig. 15
14 an arrangement for such electrodes 74 and 75 is
15 illustrated. These electrodes can preferably be divided
16 into several sections along the waveguides. This type of
17 electrodes can also be used to indirectly modulate the
18 light.

19 When fabricating laser diodes a certain variation in
20 the output wavelength is obtained. To get the specific
21 wavelength required for phasematching, the well-known
22 technique of cooling or heating the diode laser can be
23 used.

24 Nonlinear optical materials useful in this context
25 include: LiNbO_3 , LiNbO_3 doped with e.g. MgO ($\text{MgO}:\text{LiNbO}_3$) or
26 with Nd and MgO ($\text{Nd}:\text{MgO}:\text{LiNbO}_3$), LiTaO_3 , LiIO_3 , KDP , KTP
27 (KTiOPO_4), with KTP isomorph crystals such as KTiOAsO_4 ;
28 furthermore: KNbO_3 , BBO ($\beta\text{-BaB}_2\text{O}_4$), LBO (LiB_3O_5), NYAB
29 (Neodymium Yttrium Aluminumborate) och CMT (Cadmium Mercery
30 Telluride). Also organic crystals, such as $m\text{-NA}$, MNA , MAP ,
31 POM , MNMA , COANP , NPP , DAN , DANS , PNP , and also polymer
32 materials and semiconductor materials, for instance GaAs
33 and InP are of interest.

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1 Waveguide resonators can be used to improve the
2 conversion efficiency for the frequency conversion. Such a
3 resonator could either be a standing wave (Fabry-Perot)
4 device or a ring resonator, and would be necessary for the
5 function in the case of (degenerated) parametric
6 oscillation. A Fabry-Perot resonator can be realized by
7 providing mirrors on the end-faces of the waveguide or
8 with grating reflectors along the waveguide. In Fig. 15
9 the upper channel waveguide 91 is arranged as a
10 Fabry-Perot resonator with mirrors on the endfaces. The
11 lower channel waveguide 92 is arranged as a resonator
12 using grating reflectors 62 and 63 etched into the surface
13 of the waveguide.

14 For certain applications it could be useful to adapt a
15 short optical fiber to the output face of the main channel
16 waveguide to be able to transfer the light to a desired
17 position.

18 In the examples above of the embodiments of the
19 invention the emphasis in the description has been on
20 conversion to shorter wavelengths: primarily conversion to
21 visible light from semiconductor laser wavelengths in the
22 near infrared wavelength region. As mentioned previously,
23 conversion to longer wavelengths for other applications,
24 can be obtained with the same type of components, and with
25 analogous methods; for instance from the usual
26 semiconductor wavelengths to longer wavelengths in the
27 infrared wavelength region. An example is
28 difference-frequency generation of the wavelength $2.1 \mu\text{m}$
29 by using pump sources at $0.8 \mu\text{m}$ and $1.3 \mu\text{m}$.

30 In the detailed description above the pump light
31 sources where in most cases referred to as semiconductor
32 lasers. The invention can obviously also be used in
33 combination with other coherent pump light sources. One
34 such example is so-called semiconductor laser pumped solid

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1 state lasers, which also are comparatively small and
2 compact. Another alternative is semiconductor laser pumped
3 fiber lasers.

4 In some parts of the description above the term light
5 should be interpreted as covering also invisible
6 radiation: infrared and ultraviolet radiation.

Patent claims

1
2 1. A device in the form of a coherent light source
3 based on frequency conversion of radiation from lasers,
4 especially easily available diode lasers, whereby said
5 frequency conversion is accomplished in optical waveguides
6 (10), (90), arranged in a substrate (1) of a nonlinear
7 material like LiNbO_3 , doped LiNbO_3 , LiTaO_3 , LiIO_3 , KDP,
8 KTP, KTiOAsO_4 , KNbO_3 , BBO, LBO, NYAB, CMT, or similar
9 materials, said device characterized in that two lasers
10 (20), (21) are utilized to generate a new laser frequency
11 through frequency mixing (sum- or difference-frequency
12 generation) and in that the two lasers emit radiation at
13 wavelengths such that the so-called phase-matching
14 condition for the optically nonlinear frequency mixing is
15 fulfilled in the said waveguide (10), (90).

16
17 2. A device according to claim 1, characterized in that
18 the waveguides are designed in such a way, and the two
19 lasers are chosen in such a way, that the wavelengths of
20 their radiation enable fulfilment of the said
21 phase-matching condition by utilization of the
22 birefringence of the crystal material in combination with
23 the waveguide dispersion.

24
25 3. A device according to claim 1, characterized in that
26 the channel waveguide where the frequency mixing takes
27 place is provided in the form of a so-called
28 quasi-phase-matching waveguide (90), whereby the
29 periodicity of the waveguide is chosen in such a way,
30 according to known principles, that the phase-matching
31 condition for the frequency mixing is fulfilled through
32 quasi-phase-matching.

33
34 4. A device according to claim 1 and 2, or according to
35 claim 1 and 3, characterized in that the frequency mixing

1 in a waveguide (10), (90), according to claim 1, is
2 combined with frequency conversion of radiation from the
3 pump sources each individually (or a part of their power),
4 preferably in separate channel waveguides (91), (92),
5 whereby the last-mentioned frequency conversion is
6 accomplished in the form of frequency doubling or by down
7 conversion in frequency by parametric oscillation, so that
8 in this way totally three or four new wavelengths can be
9 generated.

10

11 5. A device according to claim 1 and 2, or according to
12 claim 1 and 3, or according to claim 1 and 4,
13 *characterized in that* the channel waveguides
14 (10), (90), (91), (92), in which the optically nonlinear
15 frequency conversion takes place, are combined, coupled
16 together or coupled apart by use of integrated optical
17 components (40), (41), (42), ... (49), which are based on
18 known technique and can be wavelength selective and
19 electrically controllable (using the so-called
20 electro-optic effect), in order to couple the radiation
21 into, out of and between the channel waveguides, in which
22 the frequency conversion takes place, and to realize exact
23 adjustment to fulfil the phase-matching condition, so that
24 in this way it is possible with electrical control signals
25 to vary the properties of the light source (alternatively
26 is possible to design a device with certain predetermined
27 properties) in one or several of particularly the
28 following regards: select one wavelength from a number of
29 available wavelengths (which are comprised of the pump
30 wavelengths and new wavelengths generated in the device),
31 vary the intensity of the light source, separate and
32 direct the radiation at the different available
33 wavelengths to different output channel waveguide ports
34 (80), (85), (81), (86), (87) and vary the intensity at the
35 different wavelengths, direct radiation at different

1 wavelengths into one common output waveguide ((85) in
2 Figs. 14 and 15) or into adjacent output waveguides ((85),
3 (86), (87) in Fig. 13), and control the relative
4 intensities or the colour balance between a number of
5 wavelength components comprised in the light source.

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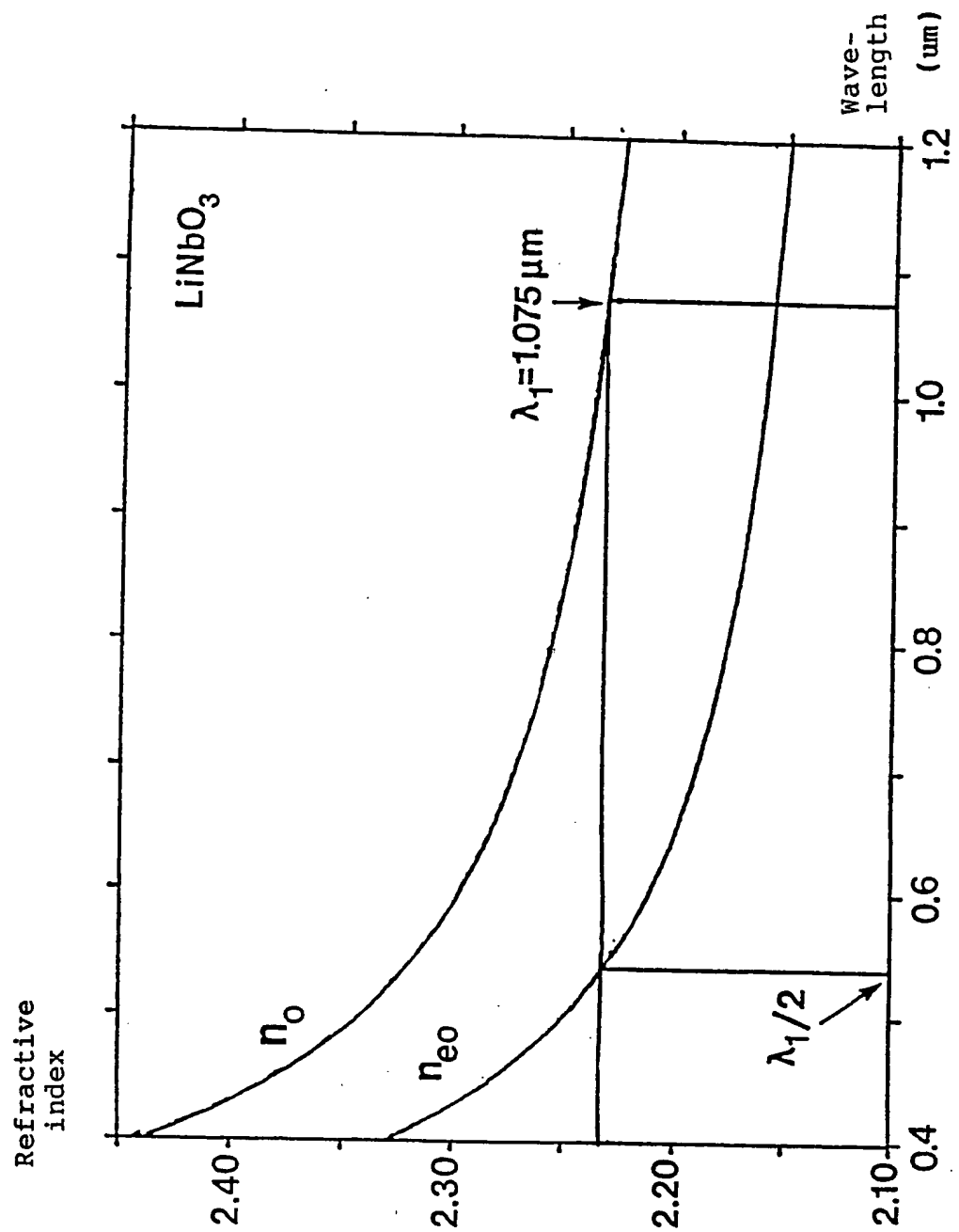
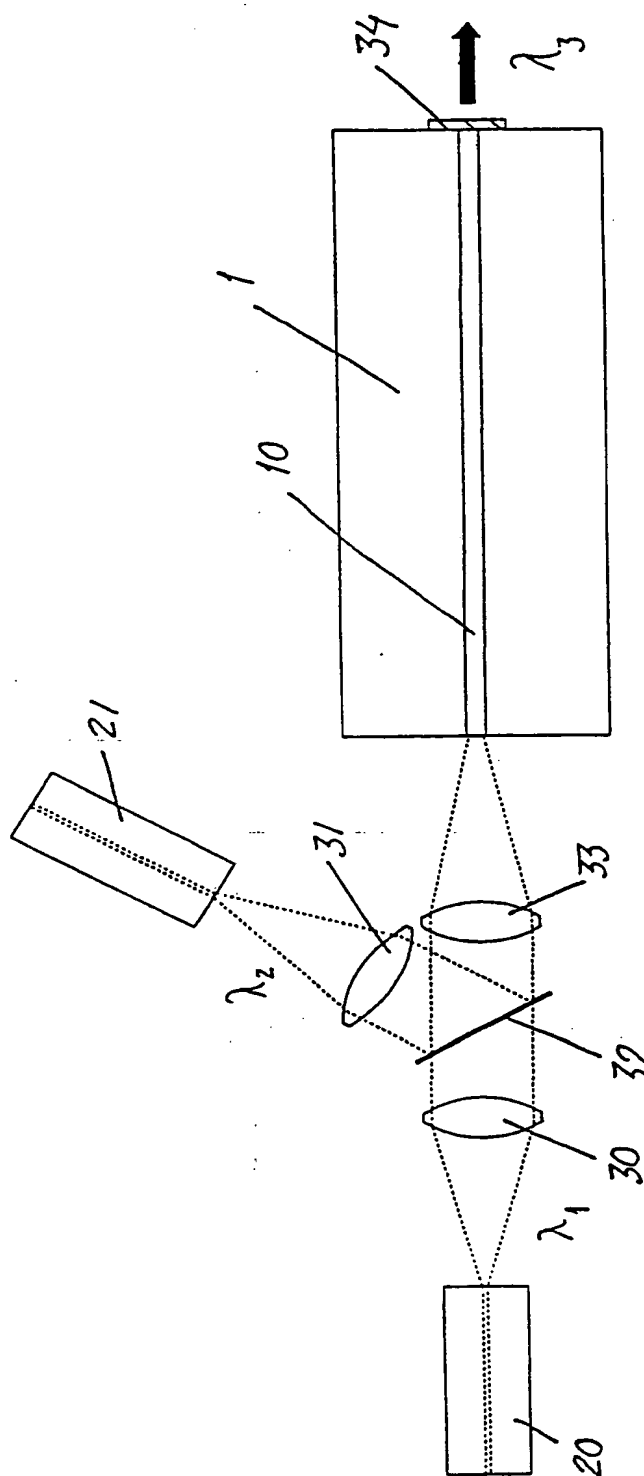


Fig. 1

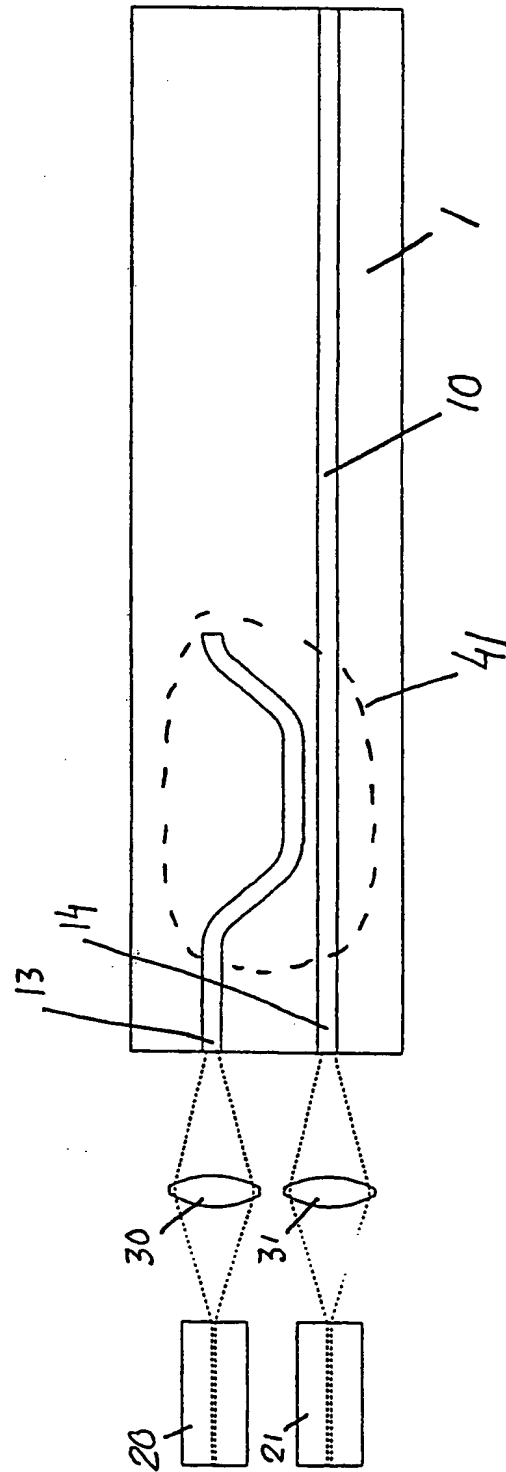
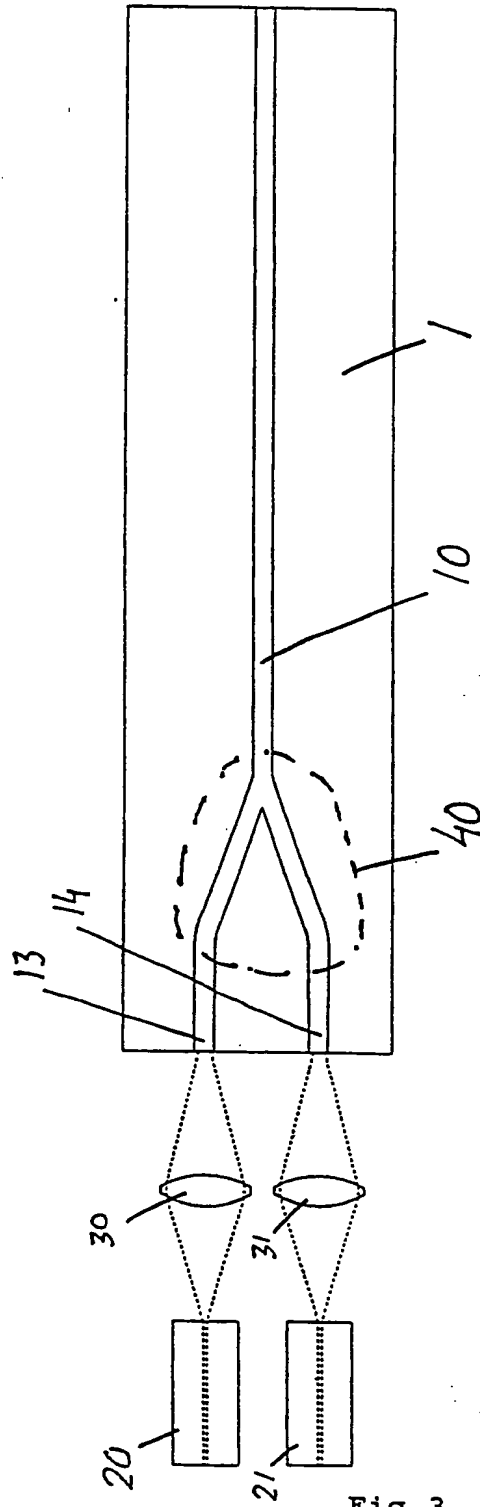
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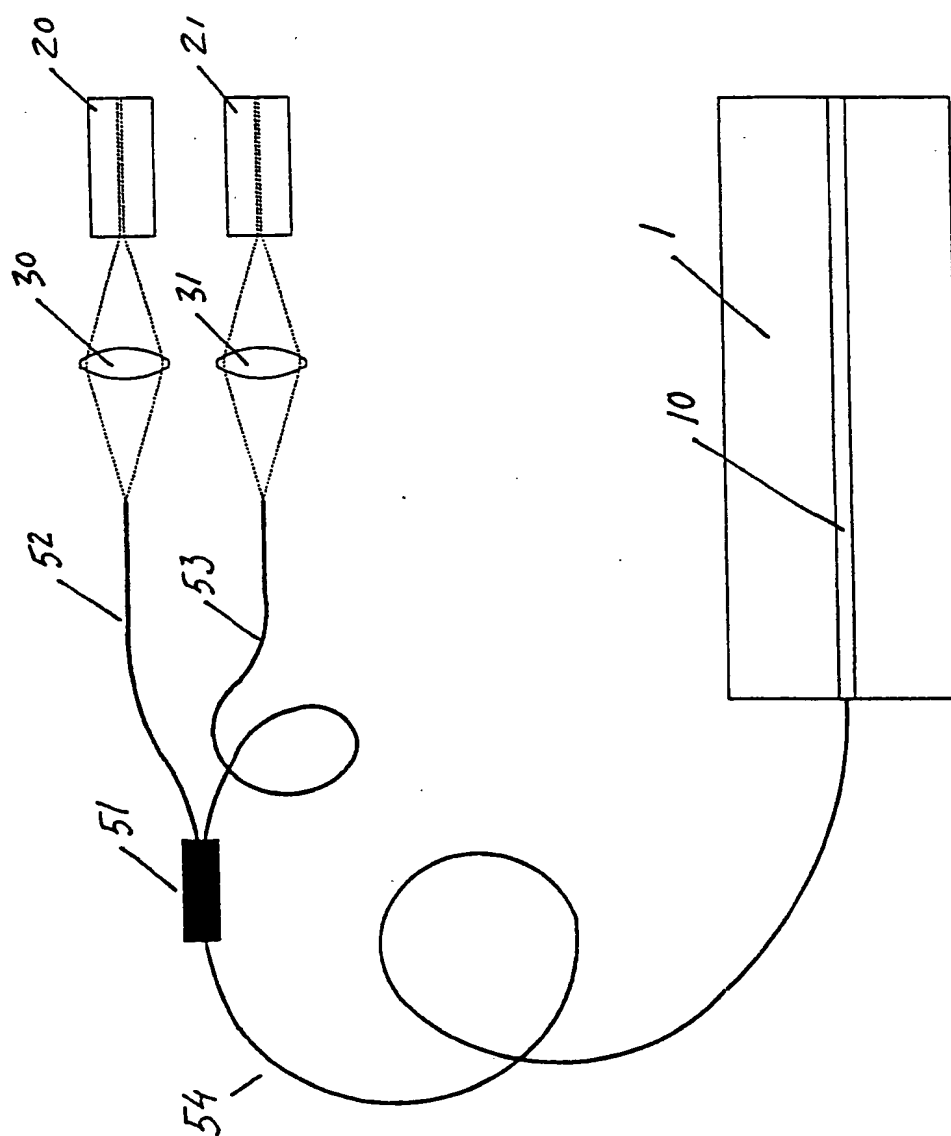
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Fig. 2



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Fig. 5
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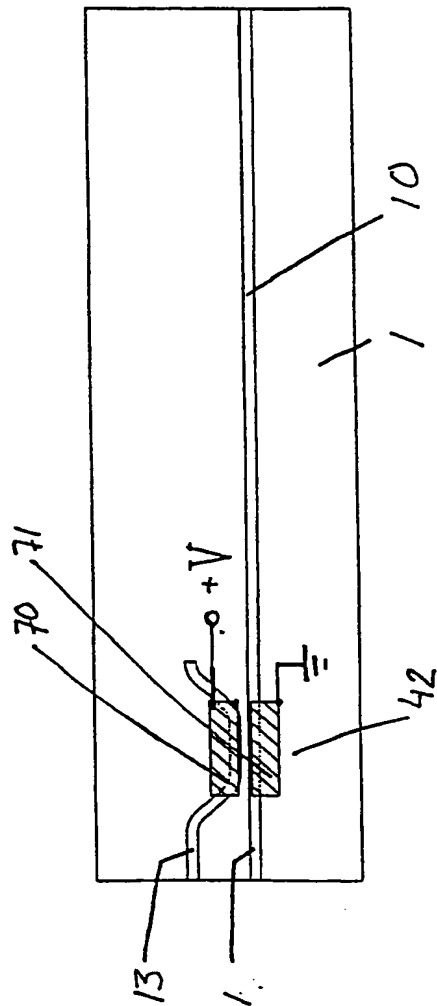


Fig. 6

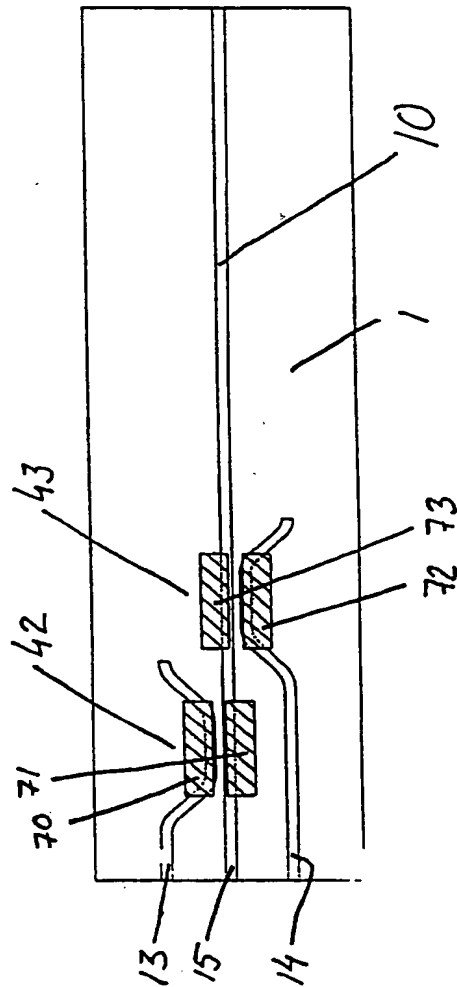


Fig. 7

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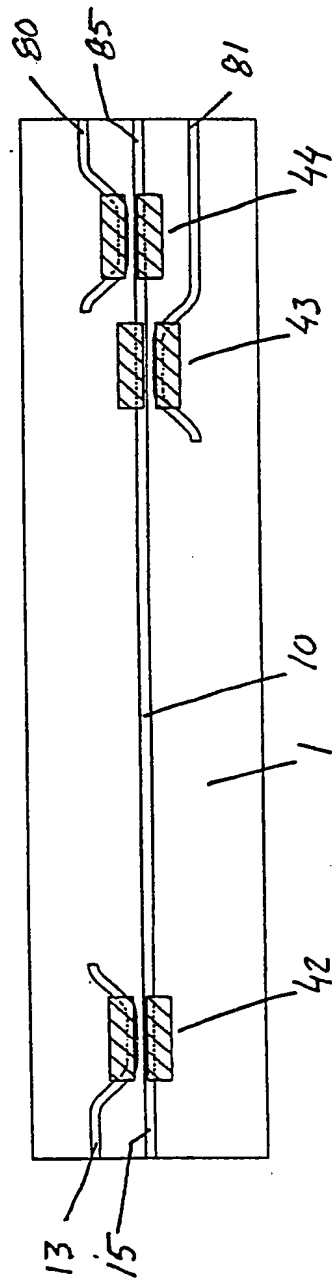


Fig. 8

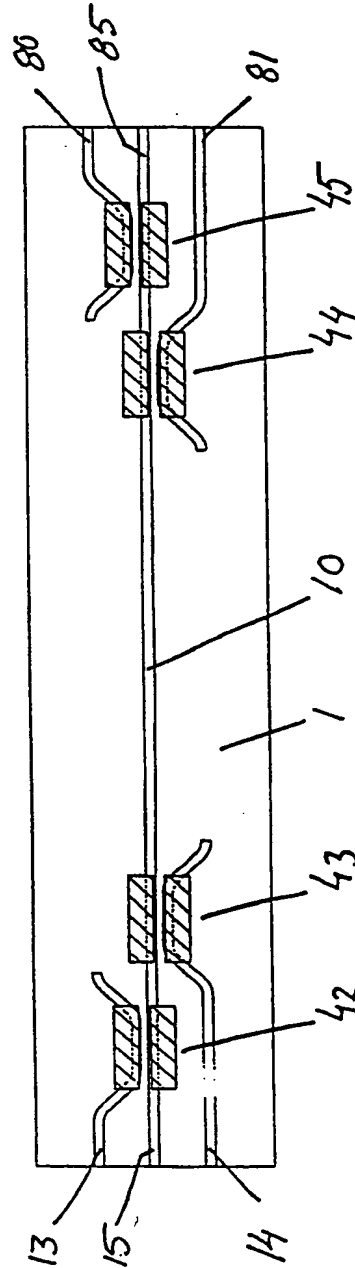


Fig. 9

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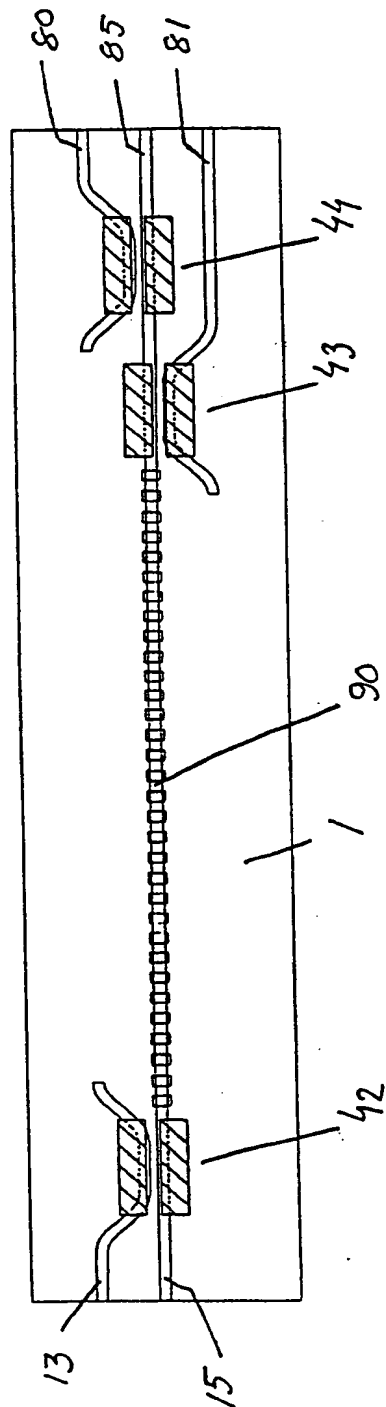


Fig. 10

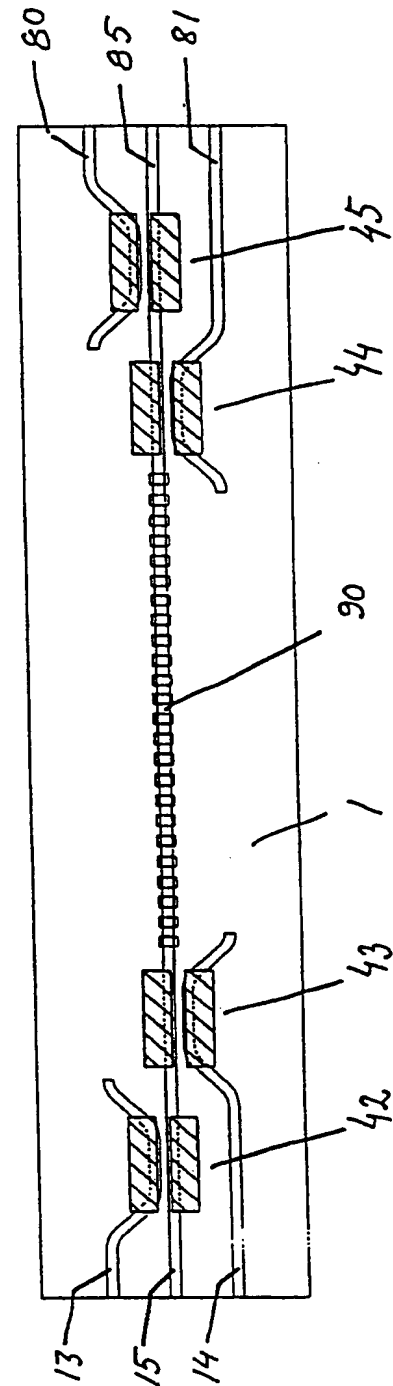


Fig. 11

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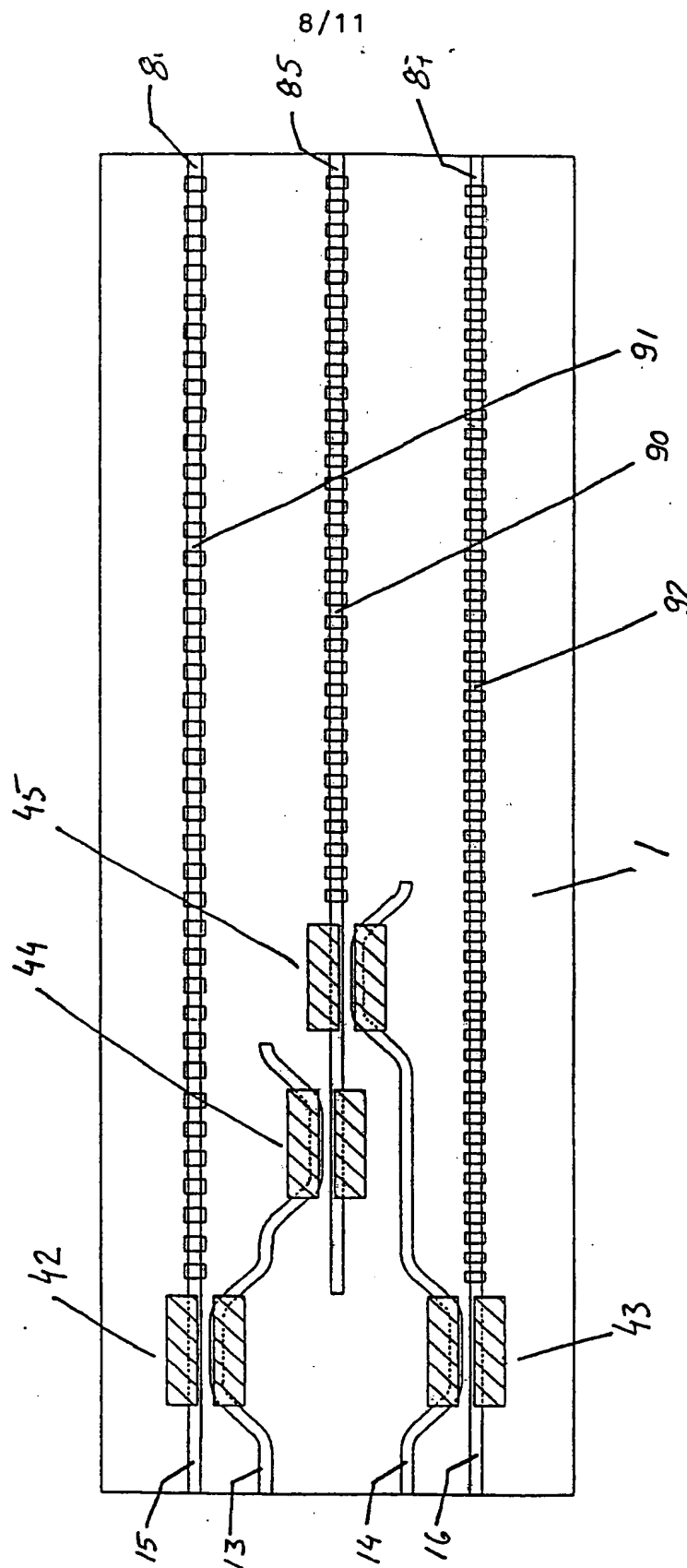


Fig. 12

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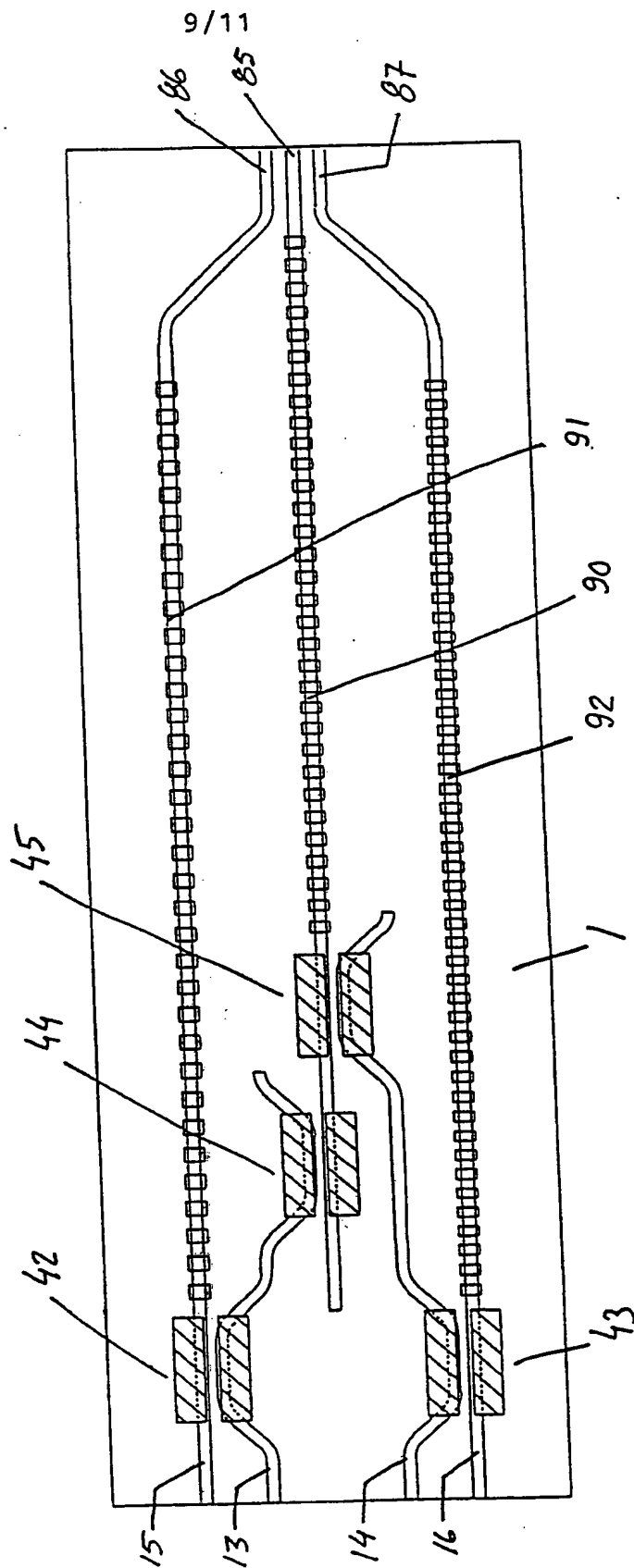


Fig. 13

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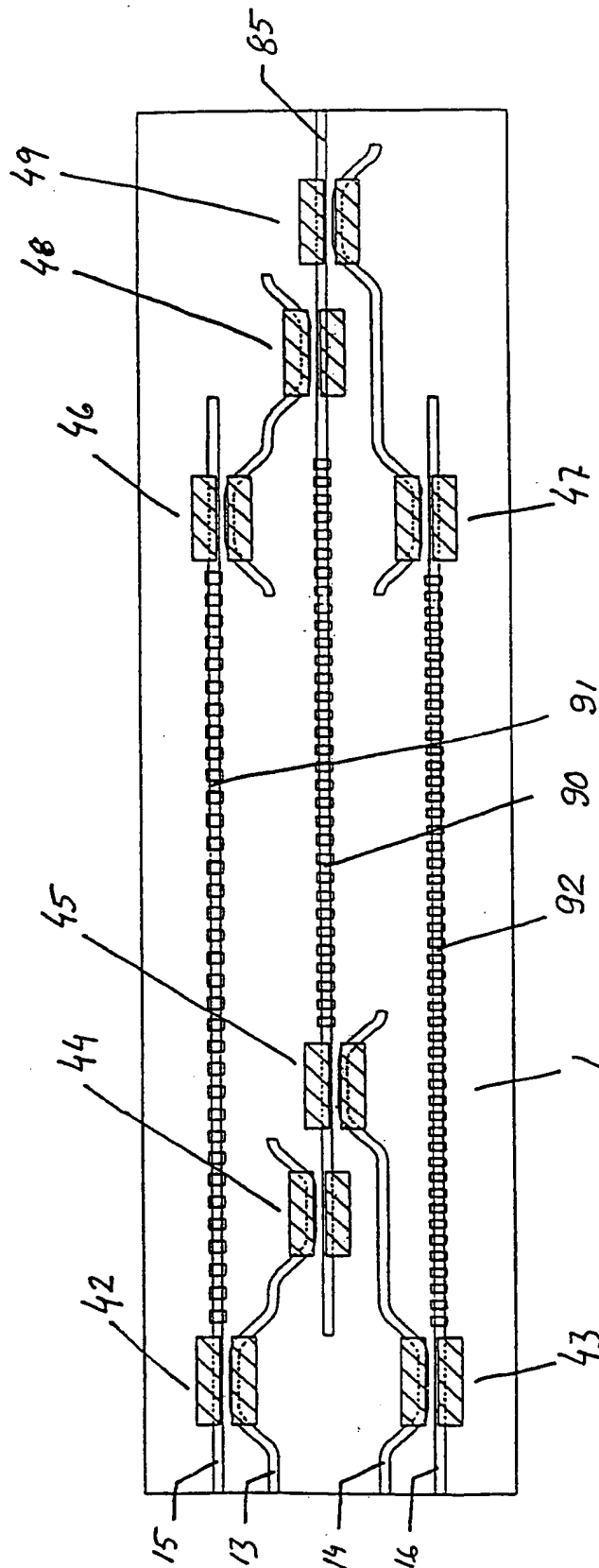
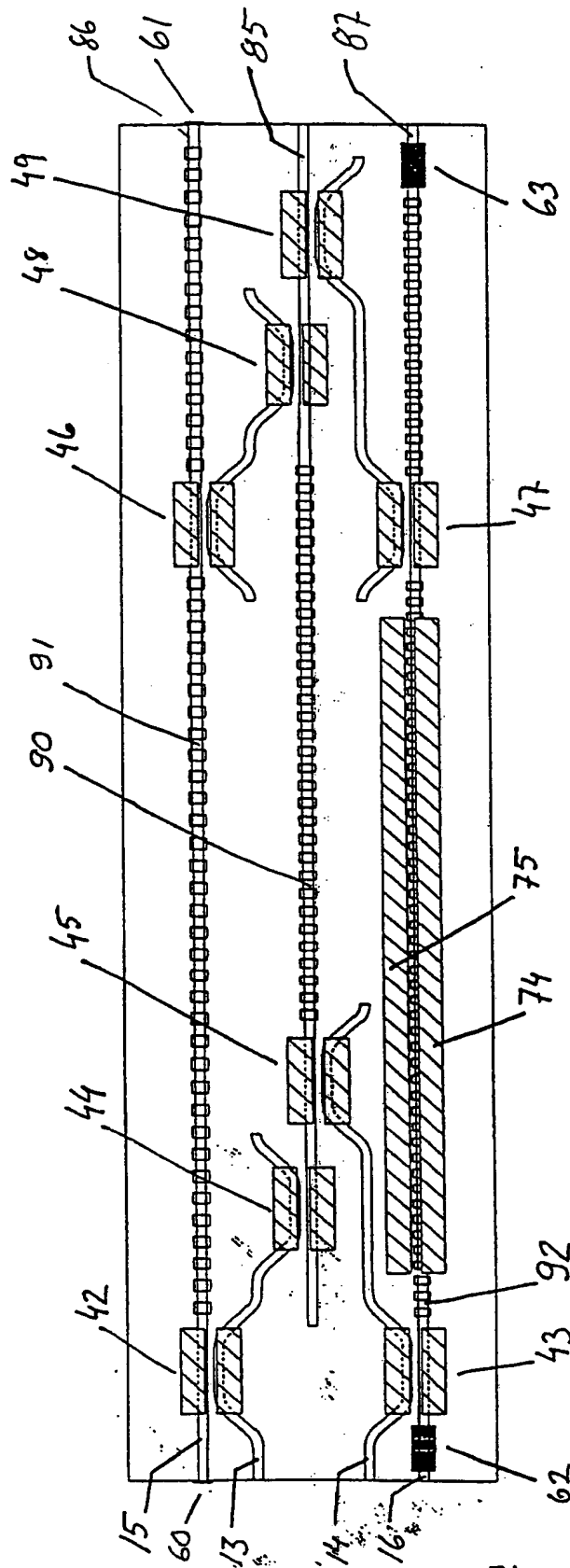


Fig. 14

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INTERNATIONAL SEARCH REPORT

International Application No PCT/SE 91/00095

I. CLASSIFICATION OF SUBJECT MATTER (If several classification symbols apply, indicate all) ⁶ According to International Patent Classification (IPC) or to both National Classification and IPC IPC5: G 02 F 1/35, H 01 S 3/13													
II. FIELDS SEARCHED <div style="text-align: center; border: 1px solid black; padding: 2px;">Minimum Documentation Searched⁷</div> <table style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 20%; border: 1px solid black; padding: 2px;">Classification System</th> <th style="border: 1px solid black; padding: 2px;">Classification Symbols</th> </tr> <tr> <td style="border: 1px solid black; padding: 5px; vertical-align: top;">IPC5</td> <td style="border: 1px solid black; padding: 5px; vertical-align: top;">G 02 F, H 01 S</td> </tr> </table> <div style="text-align: center; border: 1px solid black; padding: 2px;">Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in Fields Searched⁸</div> <p style="padding: 5px;">SE,DK,FI,NO classes as above</p>			Classification System	Classification Symbols	IPC5	G 02 F, H 01 S							
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IPC5	G 02 F, H 01 S												
III. DOCUMENTS CONSIDERED TO BE RELEVANT⁹ <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%; padding: 2px;">Category *</th> <th style="width: 60%; padding: 2px;">Citation of Document,¹¹ with indication, where appropriate, of the relevant passages¹²</th> <th style="width: 30%; padding: 2px;">Relevant to Claim No.¹³</th> </tr> </thead> <tbody> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">A</td> <td style="padding: 5px;">EP, A1, 0256964 (TECHNION RESEARCH & DEVELOPMENT FOUNDATION) 24 February 1988, see the whole document --</td> <td style="text-align: center; vertical-align: top; padding: 5px;">1-5</td> </tr> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">A</td> <td style="padding: 5px;">APPLIED OPTICS, Vol. 17, No. 5, March 1978 S. BLIT ET AL: "CONTINUOUS WAVE UV RADIATION TUNABLE FROM 285 NM TO 400 NM BY HARMONIC AND SUM FREQUENCY GENERATION", see page 721 - page 723 -- -----</td> <td style="text-align: center; vertical-align: top; padding: 5px;">1-5</td> </tr> </tbody> </table> <div style="padding: 5px;"> <table style="width: 100%;"> <tr> <td style="width: 50%; vertical-align: top;"> <p>* Special categories of cited documents:¹⁰</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </td> <td style="width: 50%; vertical-align: top;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&" document member of the same patent family</p> </td> </tr> </table> </div>			Category *	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³	A	EP, A1, 0256964 (TECHNION RESEARCH & DEVELOPMENT FOUNDATION) 24 February 1988, see the whole document --	1-5	A	APPLIED OPTICS, Vol. 17, No. 5, March 1978 S. BLIT ET AL: "CONTINUOUS WAVE UV RADIATION TUNABLE FROM 285 NM TO 400 NM BY HARMONIC AND SUM FREQUENCY GENERATION", see page 721 - page 723 -- -----	1-5	<p>* Special categories of cited documents:¹⁰</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&" document member of the same patent family</p>
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IV. CERTIFICATION <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%; border: 1px solid black; padding: 5px;"> Date of the Actual Completion of the International Search 22nd April 1991 </td> <td style="width: 50%; border: 1px solid black; padding: 5px;"> Date of Mailing of this International Search Report 1991 -05- 02 </td> </tr> <tr> <td style="border: 1px solid black; padding: 5px;"> International Searching Authority <div style="text-align: center; padding-top: 10px;">SWEDISH PATENT OFFICE</div> </td> <td style="border: 1px solid black; padding: 5px;"> Signature of Authorized Officer <div style="text-align: center; padding-top: 10px;">RUNE BENGTSSON</div> </td> </tr> </table>			Date of the Actual Completion of the International Search 22nd April 1991	Date of Mailing of this International Search Report 1991 -05- 02	International Searching Authority <div style="text-align: center; padding-top: 10px;">SWEDISH PATENT OFFICE</div>	Signature of Authorized Officer <div style="text-align: center; padding-top: 10px;">RUNE BENGTSSON</div>							
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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